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DIFFERENTIAL ELECTRON SCATTERING MEASUREMENTS
IN HELIUM FOR SLOW ELECTRONS

by

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I.

INTRODUCTION

The study of the physical processes involving collisions between electrons and atoms are of interest in a number of fields of physics (plasma physics, atmospheric physics and astrophysics). These processes can be separated into two general classes; elastic and inelastic interactions. The inelastic processes are characterized by a loss of energy of the incident electron and subsequent change in the structure (excitation or ionization) of the atom. The measurement of scattering cross sections, which characterize these processes, have been the subject of systematic investigations since the 1920's. The first measurements involving electron-atom collisions provided total cross sections describing the collisions but as quantum mechanical calculations describing the collision processes began it became apparent that total cross section measurements did not provide sufficient sensitivity to guide further theoretical refinements. Thus the early measurements of the angular distribution of scattered electrons were undertaken to provide more rigorous tests of theoretical calculations.

After the initial period of vigorous study limited attention, both theoretically and experimentally, was given to electron-atom collisions. However with the advent of high speed computers

and major advances in experimental technology, the study of electron-atom collision processes has within the past three decades, again become a vigorous experimental and theoretical area. Ultra high vacuum technology and high energy resolution electron beam monochromators and analysers are among the major advances which have made this rebirth possible. More recently coincidence techniques, long a tool in nuclear physics, have been applied to measurements in atomic physics and have provided additional information about the scattering processes.

The measurements reported here comprise a study of the angular distribution of electrons scattered by helium for selected energies between 18 and 80eV. Helium was chosen as the target atom because it is well suited to testing a new experimental apparatus. Helium has the advantages that it is inert, easy to work with, and has been studied extensively. The measurements that have been made, include differential elastic scattering cross sections and differential inelastic (2^3S, 2^1S, 2^3P and 2^1P) excitation cross sections for incident energies of 50 and 80eV. An angular study of the energy dependent structures in the elastic cross section over the energy range 18eV to 25eV is also presented. Finally, the results of an angular correlation experiment of the 2^1P state yielding the ratio (λ) of the excitation cross sections for the $m_J=0$ to the total differential excitation cross section are presented for an impact energy of 80eV.

The history of experimental and theoretical studies of electron-helium collision processes is certainly an extensive one.

In general, these studies may be roughly separated into slow, intermediate and fast collisions depending upon the relative magnitude of the incident electron velocity (v_i) and the orbital electron velocity (v_0). For electron helium collisions the slow region ($v_i \leq v_0$) extends to an incident energy of approximately 100eV. Intermediate ($v_0 \leq v_i \leq 3v_0$) and fast ($v_i \geq 3v_0$) collisions cover the energy ranges ($100 \leq E \leq 900$) and ($E \geq 900$), respectively. The discussion of the previous studies of angular distribution measurements for slow collision processes will be separated into four categories: differential elastic cross sections, differential n=2 excitation cross sections, negative ion resonances and cusps in the neighborhood of the n=2 excitation threshold and electron-photon coincidence studies.

Differential elastic cross sections for incident energies below the first excitation threshold were first measured by Ramsauer and Kollath[1] and Bullard and Massey.[2] Of the recent measurements in the slow collision energy range[3-6] those of McConkey and Preston[5] and Srivastava and Trajmar[6] have extended the measurements to energies above the first excitation threshold. Of the measurements[7-16] which overlap the slow collision regime only those of Hughes et al.,[7] Mohr and Nicoll,[8] Williams[11] and Crooks[12] report energies below 100eV.

Theoretical calculation of the differential elastic cross sections for slow collisions have employed a variety of techniques. Examples of calculational methods which have been investigated include the polatized orbital method of LaBahn and Callaway,[17,18] close coupling techniques of Winters et al.,[19] and McCarthy, et al.[20]

Second order Born approximation of Buckley and Walters[21] and an adiabatic polarization potential approximation of Khare and Moiseiwitsch.[22] The use of the Glauber and other Eikonal type approximations have recently been reviewed by Gerjiory and Thomas.[23]

Experimental measurements[24-40] of the differential excitation cross sections for the n=2 states in the slow collision regime have not been as extensive as the differential elastic cross sections. Early notable measurements were reported by Mohr and Nicoll.[24-25] Of the later measurements the work of Trajmar and co-workers[26-31] were among the first high resolutions studies of the differential excitation cross section. Measuremernts covering large angular ranges have been reported by Crooks,[35,36] Opal and Beaty,[37] Hall et al.,[38] Chutjian and Srivastava[39] and Yagishita et al.[40] Measurements have also been reported by Vriens et al.,[32] Lassettre et al.,[33] and Chamberlin et al.,[34] but these are limited to scattering angles of less than 30^0.

Theoretical calculations of the differential excitation cross sections for slow collision have been calculated using various approximations. The recent reviews of McDowell[41] and Rudge[42] survey the calculational techniques for the slow and intermediate energy regimes. Examples of these methods include the distorted wave calculation of Madison and Shelton[43] and Scott and McDowell,[44,45] eikonal type calculations[17] of Yates and Tenney,[46] Flannery and McCann,[47,48] and Bryan and Joachain,[49] Coulomb projected Born approximation of Hidalgo and Geltman,[50] random phase approximation of Thomas et al.,[51] and close coupling techniques techniques of Bransden and co-workers[52-56] and Ormonde and Golden.[57]

Experimental and theoretical investigations of negative ion resonances and cusps in the neighborhood of the n=2 threshold have been the subject of intense investigation since the first unambigious observation by Schulz.[58] The motivation for Schulz's search for resonances in the elastic cross section below the 2^3S excitation threshold was the hypothesis by Baranger and Gerjuoy[59] that the structure observed in the metastable threshold excitation cross section[60] could be due to the formation of a compound (He^-) state. Using the Breit-Wigner formula Baranger and Gerjouy were able to obtain a very good fit to the structure below the opening of the 2^3P channel. They argued that if a compound state was formed there should also be a decay channel back to the 1^1S ground state which would be observable in the elastic scattering channel and provide an unambigious test of the compound state hypothesis. Within the ensuing ten years prior to Schulz's[61] review of resonances, as many as 19 additional energy dependent structures had been observed in helium in the elastic and n=2 excitation scattering cross sections. The experimental confirmation of the S-wave identification of the 19.3 volt resonance by Ehrhardt and Muster[62] was made by analysing the angular dependence of the resonance. Among the early "resonance search" measurements were the first observations of Wigner cusps[63] at the thresholds of the 2^3S and 2^1S states observed by Kuyatt el al.,[64] in a transmission experiment.

Reviews of the theoretical descriptions and calculational techniques describing resonances have been given by Burke[72,73] and Smith.[74] As pointed out by Nicolsudes[75] the calculation of energies

and widths of resonances may be divided into three categories characterized by the interpretation of the resonance process. The close coupling technique exemplifying the "scattering point of view" where the resonance is identified as an abrupt change by about π in the energy dependent phase shift. The second category interprets the resonance as a decaying state and the third as a special type of bound state. Examples of theoretical approaches and calculational techniques include Burke et al.,[76] Oberon and Nesbit,[77] Bain et al.,[78] Berrington, et al.,[79] and Hata.[80] Several descriptions and calculations of the shapes of the Wigner cusps have been reported.[66,81-86] The principle technique for determining the shape of the cusps is the evaluation of the analytic nature of the scattering matrix in the vicinity of the threshold. The calculation of cusps have also been done as the byproduct of calculations whose principle aim has been the calculation of resonance positions and widths.[76,77,79]

Delayed coincidence techniques have long been used in nuclear physics;[87] however, they have only recently been adapted to atomic collision measurements. The initial uses of delayed coincidence techniques using pulsed electron beams were directed at measurements of atomic lifetimes.[88] Several reviews of coincidence techniques and their application to atomic and molecular lifetime measurements have been given.[89-91] Coincidence techniques were later applied to the study of electron impact ionization of helium[92] by detecting the scattered and ejected electrons in coincidence and thus giving a full kinematic description of the collision process. In the first reported electron-photon coincidence experiment[93] the

cascade free lifetime of the 4^1S state in helium was measured. Later the method was used to make absolute differential excitation cross section measurements[94] of unresolved levels within the n=4,5 manifolds. The first electron-photon coincidence measurement with photon polarization analysis[95] was undertaken to show that the emitted radiation is completely polarized. The most recent and perhaps the most significant application of the coincidence technique applied to measurements of scattering processes is the evaluation of magnetic substate scattering cross sections and relative phase between the excitation amplitudes.[96-103] The pioneering measurements of Eminyan et al.,[96-98] were soon followed by further electron-helium collision measurements [99,100,101] and extension of the technique to argon[102] and neon.[100] Recently Kleinpoppen[103] has reviewed the measurements of the Sterling group and emphasized the benefits of the Stokes parameter formulation.

The first consistent theoretical description of the polarization of atomic line radiation excited by electron impact was given by Pecival and Seaton.[104] However, this is a time independent theory and with the advent of particle-photon coincidence measurements, it became necessary to consider the time dependence of the radiation. The theory of Macek and Jaecks[105] provided the first consistent time dependent description of collisionally excited line radiation which connects the anisotropy of the emitted radiation to the conherent excitation of the magnetic substates of the excited level. The theory was then reformulated by Fano and Macek[106] to stress the intrepretation of observed anisotropy in terms of alignment and orientation of the emitting atoms. Other treatments have been

have been given by Rubin et al.,[107] Wykes,[108] Blum and Kleinpoppen[109] and Eichler and Fretsch.[110] The calculations of the magnetic substate cross sections and relative phase between excitation amplitudes have been reported for eikonal,[47] random phase,[51] polarized orbital,[45] close coupling[55] and distorted wave[114] approximations.

The purpose of the measurements reported in this thesis were to have been two-fold. Elastic and inelastic cross sections and resonance measurements were viewed as calibration prior to further study. During the calibration phase new elastic cross section measurements[5,6] were reported which cast some doubt on the reliability of previously measured angular distributions and lead to a more thorough study of the differential elastic and inelastic cross sections. Structures visible in the resonance spectra which were not expected for the energy resolution of the apparatus also became of interest in the early phase. The coincidence measurements which represent a significant advance in the present knowledge of the electron helium collision system in the slow collision regime are also reported.

II.

THEORY

The purpose of this section is to briefly review the theory of electron atom collisions necessary for the interpretation of the electron helium scattering data presented in this thesis. The connection between the experimentally measured differential cross section $\sigma(\theta)$ and the quantum mechanically calculable scattering amplitude $f(\theta)$ is

$$\sigma(\theta) = \frac{d\sigma}{d\Omega} = |f(\theta)|^2. \tag{1}$$

This review will consist of a brief introduction to scattering theory, a qualitative discussion of resonance structure and a discussion of the interpretation of electron photon coincidence measurements. The liberal use of the excellent reviews of Mott and Massey,[111] Massey and Burhop,[112] Bates[113] and Moiseiwitsch and Smith[114] are gratefully acknowledged.

Scattering theory using the stationary state method starts with the time independent Schrodinger equation

$$H(\bar{r},\bar{r}')\ \psi(\bar{r},\bar{r}\ ) = E\,\psi\,(\bar{r},\bar{r}') \tag{2}$$

where $H(\bar{r},\bar{r}')$ is the full Hamiltonian of the system of incident particle and scattering atom, $\psi(\bar{r},\bar{r}')$ is the system wave function

and E is the total energy of the system. The full Hamiltonian is separable into the atomic $\{H(\bar{r}')\}$, free particle $(\bar{h}^2 \nabla^2/2m)$ and interaction potential $V(\bar{r},\bar{r}')$ parts as

$$H = H(\bar{r}\ ) - \frac{\bar{h}^2}{2m} \nabla^2 + V(\bar{r},\bar{r}') \qquad (3)$$

where $\bar{r}'$ and $\bar{r}'$ are the atomic and incident electron coordinates respectively. In the usual fashion the wave function $\Psi(\bar{r},\bar{r}')$ is expanded as

$$\Psi(\bar{r},\bar{r}') = S_n\ \phi_n(\bar{r}')\ F_n(\bar{r}) \qquad (4)$$

where $\phi_n(r')$ are the atomic wave functions, S_n represents a sum over discrete states and integration over the continuum states,and $F_n(\bar{r})$ describes the scattered electron.

By inserting Equations (3) and (4) into Equation (2), multiplying from the left by Equation (4) and integrating over atomic coordinates Equation (2) can be expressed as

$$(\nabla^2 + k^2m)\ F_m(\bar{r}) = \sum_n^{\infty} U_{mn}(\bar{r},\bar{r}')\ F(\bar{r}) \qquad (5)$$

where

$$k^2m = k_0{}^2 + \frac{2m}{\bar{h}^2}\ (E_0 - E_n) \qquad (6)$$

and

$$U_{mn} = \int \Psi_m^*\ (\bar{r}')\ U\ (\bar{r}',\bar{r})\ \Psi_n\ (\bar{r}')\ d\bar{r}'^3$$

where

$$U\ (\bar{r}',r) = \frac{2m}{\bar{h}^2} V\ (\bar{r},\bar{r}')$$

The solution of the infinte set of integro-differential equations in Equation (5) represents an impossible task, thus approximate solutions are introduced. The one state, Born or plane wave approximation asserts that

$$F_n = 0 \quad n \neq 0 \qquad (8)$$

and

$$F_0 = e^{i\vec{k}_0 \cdot \vec{r}} \qquad (9)$$

which reduces Equation (5) to single integro differential equation.

The distorted wave or two state approximation retains two terms (n = 0,m) from the sum which provides a correction for the distortion of the incident and scattered waves due to the field of the target atom. The close coupling approximation uses a truncated atomic eigen function expansion of Equation (4) which also renders the number of coupled integro differential equations to a manageable problem.

An alternate formulation is the method of partial wave analysis. In this formulation the incident particle wave function is decomposed into partial waves of well defined angular momentum (ℓ). If the interaction potential is spherically symmetric, the expansion is carried out in terms of Legendre polynomials. A spherically symmetric potential will be assumed but nonspherical potentials can be accomodated if the potential can be separated into an angular and a radial part and spherical harmonics are used in the expansion. The assumption of a local potential of finite range is also implied which for non-ionizing collisions is valid.

The well known partial wave representation of the scattering amplitude for potential scattering is given by

$$f(\theta) = \frac{1}{2ik} \sum_{\ell} (2\ell + 1)(e^{-2i\delta_\ell} - 1) \; (P_\ell(\cos\theta) \qquad (10)$$

where δ_ℓ is a phase shift. Here all the physics of the collision have been condensed into the phase shifts by virtue of the fact that analysis of the scattering process is only considered in the asymptotic limit and the effect of the interaction is to alter the phase of the scattered particle.

The partial wave formalism is particularly useful in describing resonant scattering below the first excitation threshold. From the "scattering point of view" the location of a resonance is defined as the point at which a phase shift abruptly changes by about π radians. If we restrict ourselves to single channel resonances, only one partial wave is effected. Thus the cross section is given by

$$\sigma(\theta) = A^2 + B^2 \qquad (11)$$

where

$$A^2 = \frac{1}{4k^2} \left| \sum_{\ell=0}^{\infty} (2\ell + 1) \; (\sin 2\delta_\ell - 1) \; P_\ell(\cos\theta) \right|^2 \qquad (12)$$

and

$$B^2 = \frac{1}{4k^2} \left| \sum_{\ell=0}^{\infty} (2\ell + 1) \; (\cos 2\delta_\ell - 1) \; P_\ell(\cos\theta) \right|^2 \qquad (13)$$

with an additional term in one of the partial waves given by[74]

$$\delta_R = -\cos^{-1}\left(2\,\frac{E - E_R}{\Gamma}\right) \qquad (14)$$

where E, E_R and Γ are the incident beam energy, resonance energy and resonance energy half width respectively. The resonance profile for the case where only the s-wave background phase shift is non-zero is shown in Figure 1. Only positive values of the phase shifts are plotted since for attractive potential scattering, as is the case in electron atom scattering, the phase shifts are positive. Here the difference between the resonance shapes is due only to the different background phases. For the case where the first three phases are non-zero, the effect of interference between the phases gives rise to the angular dependence of the resonance shown in Figure 2. Here the background phases and the resonance half width have been chosen to approximately match the values for the 2^2S resonance in helium to portray the approximate shape of the experimentally observed resonance.

The theory of electron-photon coincidence measurements of Macek and Jaecks[105] is formulated such that the interpretation of the measurement, in terms of the population of states created by the collision of the incident electron, is directly related to the experimental geometry and coincidence rate. The scattering amplitudes for excitation to these states are left as parameters to be fitted to the experimental data. At the outset it should be pointed out that the fundamental difference between normal electron scattering experiments and electron-photon coincidence experiments